Evaluation of Speech Processing for Telephone Use by Elderly Listeners with Hearing Loss

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ABSTRACT

Communicating over the telephone is a daily struggle for many older adults with hearing loss. Hearing aids and assistive listening devices improve the situation, but the vast majority of hearing-impaired elderly do not own such devices. In response to this problem, a Telephone Speech Enhancement Algorithm (TSEA) was designed through a collaborative effort of The Ohio State University Department of Speech and Hearing Science and the Department of Electrical and Computer Engineering. The TSEA uses an algorithm that pre-processes speech, such that the signal is enhanced on the talker's end before being sent across the telephone line to the listener with hearing loss. Previous research examined the effectiveness of the TSEA at improving speech intelligibility for three levels of speech perception (phoneme, word, and sentence) (Poling, 2004; Harhager, 2007), but ceiling effects in recognition were noted, possibly biasing the results.

Twelve older adults with a mild to severe sensorineural hearing loss consistent with presbycusis participated in this study. The objective of this study was to equate the level of difficulty of the three speech perception tests used to measure speech intelligibility first, before measuring the effectiveness of the TSEA at improving speech intelligibility over the telephone. Specifically, the MRT (phoneme-based test), the SPIN (word-based test), and the QSIN (sentence-

based test) were presented in two conditions: unprocessed and processed using Comunify, the platform that runs the TSEA. Multitalker babble was added to the MRT and SPIN in both the unprocessed and processed conditions in an attempt to equate the level of difficulty of the three speech intelligibility tests.

Results revealed that significant improvements in speech perception over the telephone occurred in the processed condition. MRT performance increased from 68.2% to 79.0%, SPIN performance increased from 55.2% to 79.8%, and QSIN performance improved from 49.9% to 75.0%. However, significant differences in the amount of improvement among the three tests were still noted. Specifically, the improvement due to processing for the SPIN (24.6%) and QSIN (25.1%) were significantly greater than for the MRT (10.8%).

The results of this study verify that pre-processing the telephone signal is successful at improving speech understanding over the telephone for older adults with hearing loss. In addition, equal levels of improvement in the processed condition were noted for both the SPIN and QSIN, but less improvement was noted for the MRT. Less improvement on the MRT is likely the result of the high performance exhibited in the unprocessed condition and illustrates that while the SPIN successfully equated for difficulty, ceiling effects may still be present for the MRT.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

The ability to communicate over the telephone with ease is taken for granted by many individuals. Unfortunately, telephone communication can be a daily struggle for many older adults with hearing loss. The lack of visual cues, the diminished quality of the speech signal due to both the reduced frequency range provided by the telephone as well as the noise created as the signal is transmitted across the telephone line, and monaural listening all play a part in making telephone use challenging for not only hearing-impaired individuals, but their communication partners as well. The Franklin County Ohio Office on Aging, which provides services for the elderly population living in the area, brought this issue to the attention of the Department of Speech and Hearing Science at The Ohio State University. A Telephone Speech Enhancement Algorithm (TSEA) was designed through a collaborative effort of The Ohio State University Department of Speech and Hearing Science and the Department of Electrical and Computer Engineering. The TSEA is an algorithm that pre-processes speech, such that the signal is enhanced on the talker's end before being sent across the telephone line to the listener with hearing loss.

Pilot data using the TSEA suggested that hearing-impaired elderly listeners found communicating over the phone easier when this processing algorithm was used (Poling, 2004). Previous research examined the effectiveness of the TSEA at improving speech intelligibility for three levels of speech perception (phoneme, word, and sentence) (Poling, 2004; Harhager, 2007). Unfortunately, ceiling effects in recognition were noted, possibly biasing the results. This capstone project involved a continuation of this research. The main objective was to equate the level of difficulty of the three speech tests used to measure speech intelligibility over the telephone first, before measuring the effectiveness of the TSEA at improving speech intelligibility over the telephone for three levels of speech stimuli (phoneme, word, and sentence).

1.1 Characteristics of Sensorineural Hearing Loss and Aging

Hearing loss is a prevalent condition that can be triggered by a multitude of factors such as cerumen impacting the ear canal, ototoxicity, heredity, disease, intense noise exposure, and aging, to name a few. For older adults, the most common type of hearing loss is age-related and is referred to as presbycusis.

Presbycusis results in a sensorineural hearing loss that is caused by damage to the cochlea or eighth cranial nerve. It is identified when both air and bone conduction thresholds are impaired to a similar degree. Most commonly, this type of hearing loss is due to damage to the sensory hair cells lining the inner ear. Unfortunately, sensorineural hearing losses typically cannot be treated medically or surgically. Therefore, the most effective treatment option for most patients living with a sensorineural hearing loss is the use of hearing aids or other types of assistive listening devices.

Hearing loss is also categorized in terms of severity. Hearing loss severity can be classified anywhere from mild to profound. Table 1.1 provides a closer look at how hearing impairment is classified. Typically, the greater the hearing loss, the more difficulty the individual experiences when trying to communicate.

1.2 Hearing Loss and Older Adults

Hearing loss is the third most prevalent chronic health condition among elderly individuals (American Academy of Audiology [AAA], 2007; Weinstein, 2000; Yueh, Shapiro, MacLean, & Shekelle, 2003). It is estimated that at least 25% of individuals over the age of 65 have a significant hearing loss (Yueh et al., 2003). In addition, the country is currently undergoing a significant shift in the age distribution of the population. The 65 years of age and older group is currently the fastest growing age group in the United States (AAA, 2007). In fact, the National Institute on Aging (NIA, 2008) estimates that approximately 20% of the nation's population will be 65 and older by 2030. Cruickshanks et al. (1998) measured the prevalence of hearing loss among adults between the ages of 48-92 in Beaver Dam, Wisconsin and found that approximately 46% of participants had a hearing loss. In addition, the risk of hearing loss was found to increase by approximately 90% for every five year increase in age, with 90% of subjects over the age of 80 years identified with a hearing loss (Cruickshanks et al., 1998).

Table 1.1. Classification of hearing impairment based on the PTA (in dBHL) and the degree of hearing loss associated with each level.

dB HL	Degree of Hearing Loss
< 0 to 15	None
16 to 25	Slight
26 to 40	Mild
41 to 55	Moderate
56 to 70	Moderately-Severe
71 to 90	Severe
> 90	Profound

* Adapted from Introduction to Audiology (Martin & Clark, 2003)

The oldest old age group, which consists of individuals over the age of 85, is currently the fastest growing subgroup among the older adult population and is projected to become the fastest growing age group by 2050 (Weinstein, 2000). The progressive expansion of the older adult population illustrates that individuals with hearing loss make up a significant part of the country's population, and that the prevalence of hearing loss will continue to grow for years to come.

1.3 Presbycusis

Presbycusis, which is the hearing loss associated with the aging process, is the most frequent cause of sensorineural hearing loss in the United States (Yueh et al., 2003). The aging process can create a number of anatomic as well as physiologic changes within both the peripheral and central auditory systems.

These age-related changes can affect all three parts of the ear. Specific changes to the outer ear include increased cerumen production, reduced skin elasticity, growth in the size of the pinna, and increased risk of collapsing the canal during audiological testing (Chisolm, Willott, & Lister, 2003). Middle ear changes consist of ossification of the ossicles, atrophy of the middle ear muscles and ligaments, and reduced circulation in the tympanic membrane (Chisolm, Willott, & Lister, 2003). Inner ear changes can include loss of hair cells, reduced elasticity in the basilar membrane, and loss of support cells within the organ of Corti (Chisolm, Willott, & Lister, 2003). Central auditory system changes most frequently involve degeneration of neurons in the brain as well as re-organization of synapses (Weinstein, 2000). The consequences of these inner ear and central auditory system changes can consist of reduced audibility as well as diminished temporal and frequency resolution. As a result, many older adults exhibit difficulty understanding speech, particularly in less than optimal listening environments. Humes (1996) found that the loss of audibility in the high frequencies accounted primarily for the decline in speech understanding among their older adult subjects. In addition, even when speech sounds are audible, the signal can be distorted due to deficits in temporal and frequency resolution. Dubno, Dirks, and Morgan (1984) found that older adults with normal hearing required better signal-to-noise ratios (SNRs) compared to young adults with normal hearing in order to obtain similar performance on speech recognition tasks. Additionally, older adults, regardless of whether they have normal hearing or hearing loss have been found to perform worse on time-compressed speech tests compared to their younger counterparts (Gordon-Salant & Fitzgibbons, 1997). The ability to separate a talker's voice out of existing background noise can also be diminished with age (Alain, McDonald, Ostroff, & Schneider, 2001).

1.4 Older Adults and Hearing Aids

Older adults have been found to be less likely to report a hearing handicap compared to their younger hearing-impaired counterparts, despite the fact that presbycusis is the most common cause of sensorineural hearing loss (Wiley, Cruickshanks, Nondahl, & Tweed, 2000). Hearing aids can improve the situation for those living with a sensorineural hearing loss, but less than 25% of individuals who could benefit from hearing aids actually own them (NCHAM, 2004). Popelka et al. (1998) measured the prevalence of hearing aid use among older adults with hearing loss in Beaver Dam, Wisconsin and found that while roughly 21% of participants with hearing loss owned hearing aids, approximately 30% of these individuals no longer utilized them. The age of the individual, severity of the hearing loss, and perceived disability due to the hearing impairment were significant predictors of hearing aid use with older age. Specifically, a greater degree of hearing loss and a higher self-perceived hearing handicap score measured with the Hearing Handicap Inventory for the Elderly (HHIE-S) was associated with greater hearing aid use (Popelka et al., 1998). Chia et al. (2007) found that older adults with bilateral hearing loss exhibited a lower health-related quality of life (HRQOL) compared to their counterparts without hearing loss. However, greater physical functioning scores were noted for individuals who consistently utilized hearing aids (Chia et al., 2007). A variety of factors can be attributed to this lack of seeking treatment among older adults with hearing loss. Through a study conducted in 1999, The National Council on Aging (NCA) found that financial factors were the biggest deterrent to obtaining hearing aids for individuals diagnosed with a hearing loss. With hearing aids costing thousands of dollars and the vast majority of insurance companies failing to help cover the costs, many living with a hearing loss simply cannot afford hearing aids. The stigma associated with hearing aids, as well as denial of a hearing loss, were also objections commonly cited in the survey (NCA, 1999).

1.5 Impact of Hearing Loss

Hearing impairment often causes communication breakdowns. However, the consequences of hearing loss can have detrimental effects on far more than the communication abilities of the elderly. Specifically, the elderly are faced with a multitude of stressors associated with their hearing loss. The impact of a hearing loss can negatively impact the quality of their lives including their emotional and mental health. Individuals coping with an untreated hearing loss exhibit a greater degree of depression, anxiety, paranoia, and insecurity in addition to a decline in social activity (NCA, 1999). Instrumental activities of daily living such as preparing meals and managing finances also exhibit reduced functioning among the hearing-impaired (Dalton et al., 2003). This decline in the quality of life among the elderly is not limited to those suffering from the most significant hearing impairments. Social and emotional declines were noted even in individuals classified with a mild to moderate hearing loss (Mulrow et al.,1990). Ironically, hearing aids are usually invaluable at improving the situation. The NCA found that the majority of hearing aid users reported a higher quality of life than those without hearing aids, and family members of the hearing aid users expressed even greater improvements (1999).

1.6 Hearing Loss and Telephone Use

Whether it is used for social purposes, medical purposes, or informational purposes, the telephone has become an indispensable device for daily functioning. Telephone use promotes socialization, self-esteem, independent living, and feelings of security (Cray et al., 2004; Murphy, 1999). Today, the telephone can be used to complete a wide variety of tasks including socializing, bill-paying, scheduling appointments, and health monitoring (Mormer & Mack, 2003). Many people take for granted the ease with which they are able to use the telephone. Unfortunately, those with a hearing loss are typically not so lucky. Communicating effectively over the telephone can be a daily struggle for hearing-impaired individuals. Telephone communication is difficult because visual cues are lacking, the frequency range available over the telephone is limited, and the hearing acuity of the listener is impaired (Kepler, Terry, & Sweetman, 1992).

Without receiving visual cues from the speaker to follow, the older, hearing-impaired listener may find it more challenging to follow the conversation because the listener is missing the talker's facial expressions, mouth movements, and hand gestures. Visual information is particularly important among older adults with hearing loss because they are more dependent on lipreading and speechreading for speech understanding (Tye-Murray, 2004). To further complicate matters, the listener is forced to depend solely on the acoustic signal that is received only in one ear (i.e., monaural rather than binaural hearing).

The quality of the speech signal being transmitted through the telephone is also diminished. The high frequencies (above approximately 3000 Hz) are eliminated during transmission. This reduction in the bandwidth of the speech signal makes it difficult for elderly listeners with hearing loss to understand what is being said, for it is exactly these frequencies that are most commonly affected in a sensorineural hearing loss attributed to aging. In addition, frequencies below 300 Hz are also eliminated. The absence of these lower frequencies also reduces the quality of the speaker's voice, making the speech signal less natural-sounding to the listener (Rodman, 2003).

The listener's decline in hearing acuity reduces the audibility of the telephone signal. In addition, environmental factors such as the presence of background noise, as well as the amount of line noise that is transmitted to the listener's end, can have a negative synergistic effect on telephone communication. Not surprisingly, these telephone communication challenges can have a negative impact on telephone usage. In a study on telephone use, Kepler, Terry, and Sweetman (1992) found that 69% of individuals are discouraged from using the telephone because of their hearing loss. The reduction in telephone communication ability is especially devastating to the elderly listeners with hearing loss who are homebound and rely on the telephone in order to maintain their independence. Compared to young adults who use the telephone for social reasons, the elderly use the telephone with less frequency, especially for social reasons, leading to feelings of isolation (Ryan, Anas, Hummert, & Laver-Ingram, 1998). Instead, the elderly tend to limit telephone use to functional tasks (Ryan et al., 1998). Telephone communication can be a struggle not only for those with hearing loss, but their conversation partners as well. Conversation partners may try to accommodate their speech patterns for the hearing-impaired listener. Unfortunately, the elderly may feel that they are being patronized because of this, leading to decreased self-esteem (Ryan et al., 1998).

1.7 Hearing Aid Telecoils

Even with the assistance of hearing aids, telephone use can be a challenge. Holmes, Kaplan, and Yanke (1998) found that only 16% of hearing aid users were satisfied with their ability to utilize the telephone while 26% reported that they were not able to use the telephone. Many hearing aids now have an optional telecoil feature designed to assist with telephone communication. A telecoil is an induction rod that is placed inside of the hearing aid which picks up the electromagnetic signal produced by the telephone and converts it into acoustic energy (Yanz & Preves, 2003). Telecoils have the ability to reduce feedback as well as eliminate background noise in the listening environment (Yanz & Preves, 2003). However, there are several drawbacks to the telecoil. Specifically, in order for a strong signal to be induced into the hearing aid, the user must correctly position the telephone over the hearing aid. In addition, the telephone must be hearing aid compatible in order for the telecoil to work. And finally, the hearing-impaired listener must have hearing aids with a telecoil to take advantage of this technology.

1.8 Developing the Telephone Speech Enhancement Algorithm (TSEA)

One method that could potentially improve speech intelligibility over the telephone is by pre-processing the speech signal before it reaches the listener.

Terry et al. (1992) filtered speech between 300 Hz – 3000 Hz to mimic the telephone bandwidth and used both frequency shaping and frequency compression to take hearing loss into account and improve speech understanding. Significant improvements in speech understanding were measured using the California Consonant Test (CCT) in both of these two test conditions (Terry et al., 1992). Although results suggested that pre-processing the telephone signal improved speech understanding in listeners with hearing loss, some weaknesses to the Terry et al. (1992) study were noted. Specifically, the hearing-impaired subjects listened to the test tokens presented binaurally under headphones instead of listening monaurally over an actual telephone line.

In the late 1990s, the Franklin County Office of Aging (FCOA), which provides services to the elderly population living in the area, brought the issue of difficulty with telephone communication when calling the elderly to the attention of the Department of Speech and Hearing Science at The Ohio State University. The FCOA reported difficulty communicating with their older adult clients over the telephone, and wished to develop a solution to help alleviate the situation. It was their hope that a device could be developed which could be used at their end (the talkers' end) to ease their employees' difficulties when conversing with the elderly over the telephone.

Since that time, the Speech and Hearing Science and the Electrical and Computer Engineering Departments have worked together on the development of such a device. The objective of this collaboration was to develop a device that pre-processes the speech signal before it travels through the telephone line, making the signal more distinguishable to listeners with a hearing loss. This device could be placed at the location, such as the FCOA, where calls from individuals with hearing loss are received. Further, it would not require the elderly to purchase any special equipment for their telephones or to have hearing aids.

Ongoing research efforts at The Ohio State University have illustrated that such a device is feasible and practical. By simulating a hearing loss in normally hearing subjects, Natarajan (2002) developed an algorithm that takes hearing loss, as well as the limited bandwidth of the telephone, into account during telephone communication and works to keep speech sounds at a constant level, thus increasing speech intelligibility. With this algorithm, soft sounds are elevated while loud sounds are kept at a comfortable level. There were several steps involved in the creation of the speech processing algorithm. First, to provide time and frequency resolution, the speech signal was divided into 32 ms frames with a 50% overlap between frames (Natarajan, 2002). Next, Discrete Fourier Transform (DFT) was used to estimate the spectral content of the speech signal so that only frames with speech information receive additional processing (Natarajan, 2002). Third, the average spectrum levels were obtained for each critical band (Natarajan, 2002). These spectrum levels were passed through a peak detection module in which the three peaks with the greatest magnitude were selected (Natarajan, 2002). Next, gains were calculated for each channel in order to preserve spectral contrasts. The spectrum level and average thresholds of hearing were used to determine the gains at each channel

(Natarajan, 2002). Because fast variations in gain may be uncomfortable for individuals with hearing loss, gains were smoothed across frames (Natajaran, 2002). Finally, Inverse Fast Fourier Transform (IFFT) was used to transform the frames into the time domain and produce the processed speech (Natajaran, 2002).

Natarajan (2002) was able to illustrate improved speech understanding using the speech processing algorithm by passing the processed speech signal through a hearing loss simulator before it was presented to normal hearing subjects. Subsequently, Komattil (2004) expanded on this research and was able to develop an algorithm that works in real time, so that the speech signal could be pre-processed while the telephone conversation was actually taking place rather than on recorded conversations as in Natarajan's (2002) work.

Using Komattil's real-time processing, Poling (2004) performed a pilot study on four older adults diagnosed with a sensorineural hearing loss. Poling tested the effectiveness of the speech enhancement algorithm at improving telephone communication in the hearing-impaired subjects by comparing the subjects' performances on representative tests of three distinct types of speech understanding – a phoneme-based test, a word-based test, and a sentence-based SNR test. Results demonstrated that the TSEA was successful at improving speech understanding via the telephone for a small sample of older adults (Poling, 2004).

Based on the positive outcome of Poling's (2004) study, the process of commercializing the speech processing algorithm began. FutureCom Technologies, Inc., in conjunction with The Ohio State University Departments of Speech and Hearing Science and Electrical and Computer Engineering received a Phase I Small Business Innovative Research (SBIR) grant from the National Institute of Health (NIH) for the commercialization of the device. In 2007, Harhager examined the effectiveness of the commercial implementation of the speech processing algorithm (TSEA) and found that it provided equivalent improvement compared to the laboratory version of the algorithm. Unlike the laboratory version, the commercial version, using the Comunify signal processing server platform, delivers the digitized test tokens over the telephone line in real-time and has the capability to handle multiple calls simultaneously. A second objective of Harhager's (2007) study was to examine the effectiveness of the TSEA at improving speech intelligibility for three levels of speech perception (phoneme, word, and sentence). Specifically, the Modified Rhyme Test (MRT; Kreul, Nixon, Kryter, Bell, Lang, & Schubert, 1968), the revised Speech Perception in Noise Test (SPIN; Bilger, Nuetzel, Rabinowitz, & Rzeczkowski, 1984), and the Quick Speech-in-Noise Test (QSIN; Killion, Niquette, Revit, & Skinner, 2001; Killion, Niquette, Gudmundsen, Revit, & Banaerjee, 2003) were chosen as the representative speech intelligibility phoneme-based test, word test, and sentence test, respectively. The MRT and SPIN tests were presented in quiet and the QSIN was presented in multitalker babble to a group of elderly listeners with sensorineural hearing loss in two conditions: unprocessed and processed (TSEA). Harhager (2007) found differences in the amount of improvement in recognition performance based on TSEA processing across the three speech tests. Although improvements were noted for all tests in the processed condition, the greatest amount of improvement in recognition performance between the unprocessed and processed test conditions was measured with the QSIN. Smaller improvements in recognition were seen with the MRT and SPIN. However, ceiling effects were noted for both the MRT and the SPIN in the unprocessed condition, possibly biasing the results.

The main objective of the present study was to attempt to equate the level of difficulty of the three speech tests utilized in Harhager's (2007) study (MRT, SPIN, and QSIN) in order to remove potential bias and better determine the effects of the TSEA. Specifically, multitalker babble was added to the MRT and SPIN tests in both the unprocessed and processed conditions in an attempt to eliminate the ceiling effects of these tests. The effectiveness of the TSEA at improving speech intelligibility over the telephone at each level of speech (phoneme, word, and sentence) was then measured.

CHAPTER 2

METHODS

The purpose of the present study was to first equate the level of difficulty of the three speech tests (MRT, SPIN, and QSIN), and then to measure the effectiveness of the TSEA at improving speech intelligibility over the telephone at each level of speech (phoneme, word, and sentence). This chapter describes the participants, calibration, and procedures used for the study.

2.1 Subjects

Elderly individuals were recruited from the patient base of The Ohio State University Speech-Language-Hearing Clinic for this study. A recruitment letter was sent to potential subjects identified through the clinic database to inform each individual that he or she may qualify for the study. Each potential subject was then contacted by telephone to discuss the study in greater detail, as well as answer any questions that the potential subjects had.

Fourteen individuals, 5 male and 9 female, participated in the study. Testing, however, was not completed on two of the subjects due to the subjects not scoring above 50% on all three of the tests (MRT, SPIN, and QSIN). Only the data from twelve of the subjects (4 male, 8 female) were analyzed. The ages of the twelve subjects ranged from 59 to 89 years with a mean age of 73 years. All subjects were native English speakers and had a mild to severe sensorineural hearing loss in at least one ear. For the purposes of this study, a mild to severe hearing loss was defined as a Pure Tone Average (obtained by averaging pure-tone air conduction thresholds at 500, 1000, and 2000 Hz) in at least one ear ranging from 25-70 dB HL.

2.2 Stimulus Materials

Three types of speech perception tests were administered to the subjects to represent each level of speech (phoneme, word, and sentence). The MRT was chosen to represent the phoneme level, the SPIN was chosen to represent the word level, and the QSIN was chosen to represent the sentences level. All three speech perception tests are described below.

> The Modified Rhyme Test (MRT; Kreul, et al., 1968) is a closed-set test consisting of 50 items. Each item contains a set of six monosyllabic words that vary either by the initial or final consonant. The listener is required to circle which word out of the six possible responses that he heard for each individual item. A sample test set is listed below:

NEAT	HEAT
BEAT	MEAT
FEAT	SEAT

> The Revised Speech Perception in Noise Test (SPIN; Bilger et al., 1984) consists of 50 sentences. Twenty-five of the sentences are classified as high predictability sentences, meaning that the final word of the sentence is predictable based on the cues received by the other words that compose the sentence. The remaining twenty-five sentences are classified as low predictability sentences,

meaning that the final word of the sentence is not predictable based on the cues received by the other words making up the sentence. The listener is required to state the last word of each sentence. Sample high predictability and low predictability sentences are listed below:

The swimmer dove into the POOL.	(High Predictability)
The girl should consider the FLAME.	(Low Predictability)

The Quick Speech in Noise Test (QSIN; Killion et al., 2003) consists of six sentences with five key words which are scored. Each sentence is presented with varying amounts of multitalker babble. The listener is required to repeat each sentence, with each key word that is repeated being scored. Although this test was designed to measure SNR loss, it is being used to measure percent correct scores for this study. A sample sentence is listed below:

The sun came up to light the eastern sky.

2.2.1 Delivery of the Stimulus Materials

Each of the three speech perception tests (MRT, SPIN, QSIN) were digitized and stored on a computer hard drive. In the unprocessed test condition, selected test tokens were delivered across the telephone line to the subjects. For the processed test condition, selected test tokens were processed using the TSEA before being delivered across the telephone line to the subjects. The multitalker babble was presented through the audiometer in the sound field through two speakers which were located at azimuths of 0 and 180 degrees. A diagram of the testing setup is provided in Figure 2.1.

Presentation levels of the speech stimuli were dictated by the experimental set-up. In order to determine the presentation level generated by the computer and telephone line, the output levels of speech stimuli were

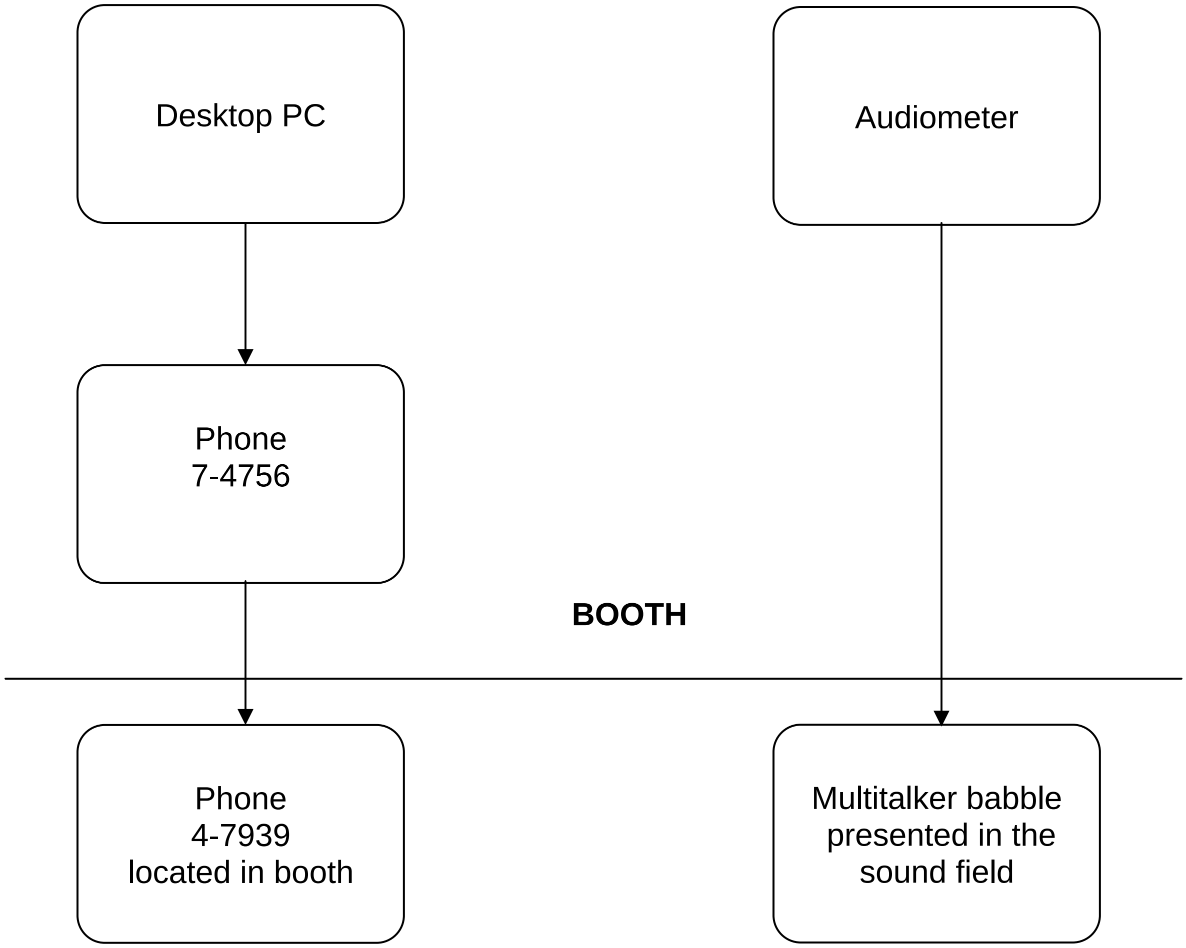

FIGURE 2.1. Diagram of testing setup using the Comunify TSEA. The telephone in the test booth (4-7939) was used to call the telephone (7-4756) attached to the desktop PC. The AC33 Interacoustic audiometer was used to present multitalker babble through sound field speakers.

measured from the telephone receiver. A sound level meter was coupled to the telephone receiver via a Knowles Electronics Manikin for Acoustic Research (KEMAR) housing a Zwislocki coupler. A 1000 Hz calibration tone for each speech test was presented through the computer to the telephone and a dB SPL output measurement was made via KEMAR. Presentation levels for the unprocessed speech tests were as follows: 70 dB SPL for the MRT and QSIN, and 74 dB SPL for the SPIN. Presentation levels for the processed speech tests were as follows: 83 dB SPL for the MRT, 85 dB SPL for the SPIN, and 82 dB SPL for the QSIN.

Multitalker babble was added to both the MRT and SPIN speech perception tests in order to equate the level of difficulty between the MRT, SPIN, and QSIN. The multitalker babble was presented in the sound field through the audiometer. The presentation levels of the speech stimuli measured via KEMAR were used to determine the various SNRs needed for each test to generate psychometric functions for unprocessed speech.

2.3 Procedure

All twelve subjects were asked to participate in two separate sessions. Both sessions were between 1-2 hours in length. The two sessions were always scheduled for different days in order to eliminate testing fatigue among the participants. Before beginning the first session, subjects were asked to read and sign two forms: the Consent for Participation in Social and Behavioral Research and the Authorization to Use Personal Health Information in Research.

All subjects were given a parking permit to use during the testing. Subjects were compensated with a monetary payment for both sessions

2.3.1 Session One

All subjects first received a complete audiological evaluation to determine if they were eligible to participate in the study. The audiologic evaluation consisted of obtaining a case history, otoscopic examination, tympanometry, conventional pure tone air and bone conduction thresholds, speech recognition thresholds, and word recognition scores. All audiologic testing was completed in a sound-treated booth. The audiometric data for each subject can be found in Appendix A. An average audiogram from the twelve subjects is shown in Figure 2.2.

After confirming that subjects met the inclusion criteria for the study (i.e., native English speakers who exhibited a sensorineural hearing loss with a PTA between 25-70 dB HL in at least one ear), the MRT, SPIN, and QSIN speech intelligibility tests were administered to each subject at three to four SNRs. The speech signal was presented at a constant level while the multitalker babble was varied. In this way, a psychometric function (percent correct by SNR) was generated for each subject for each speech intelligibility test. Figure 2.3 presents psychometric functions for two individual subjects. The top graph shows subject 10, while the bottom graph shows subject 5. Specifically, three points on the psychometric function were targeted: below 50%, near 50%, and above 50%. The 50%-correct threshold was then interpolated from each function in order to

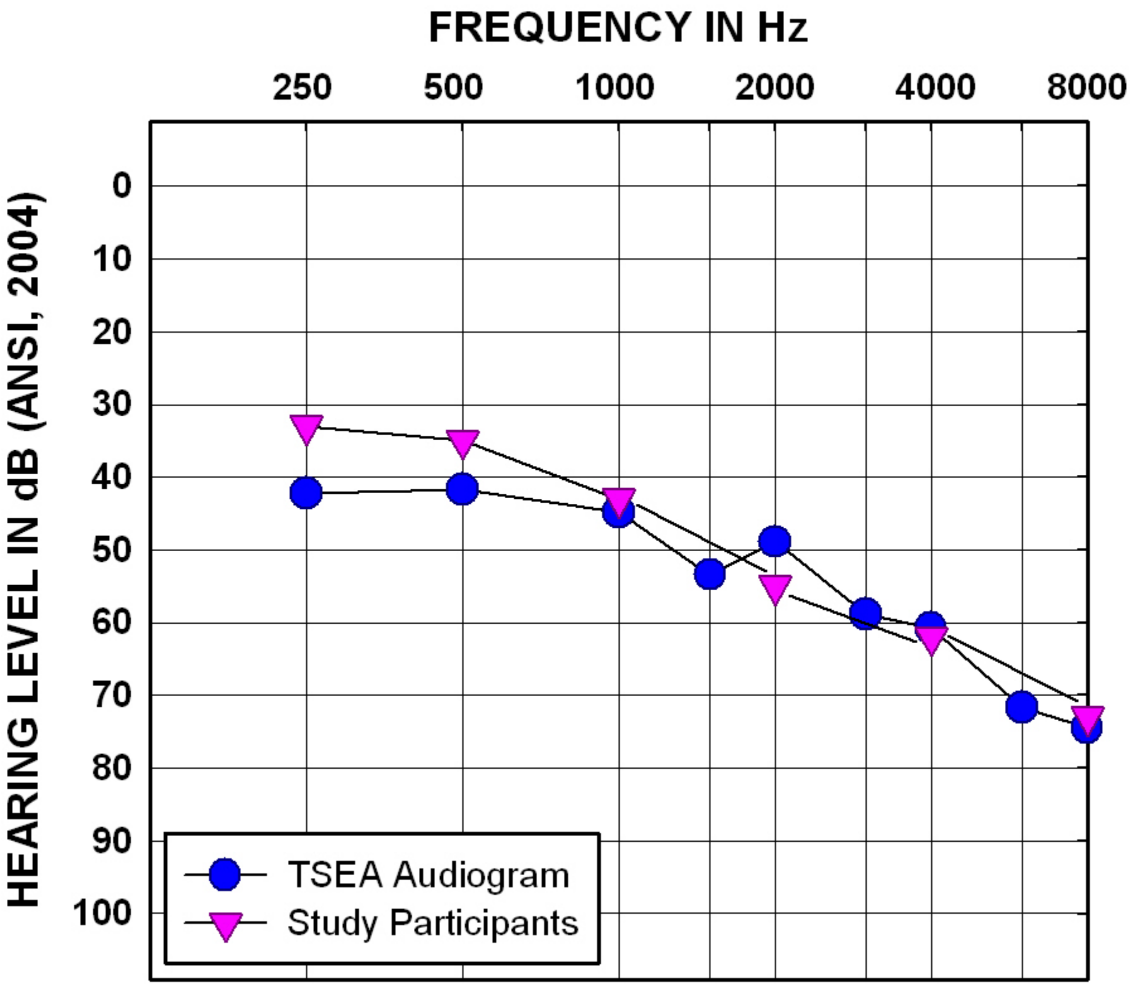

Figure 2.2. Average audiogram of the 12 test subjects compared to the audiogram used to develop the telephone speech enhancement algorithm (TSEA).

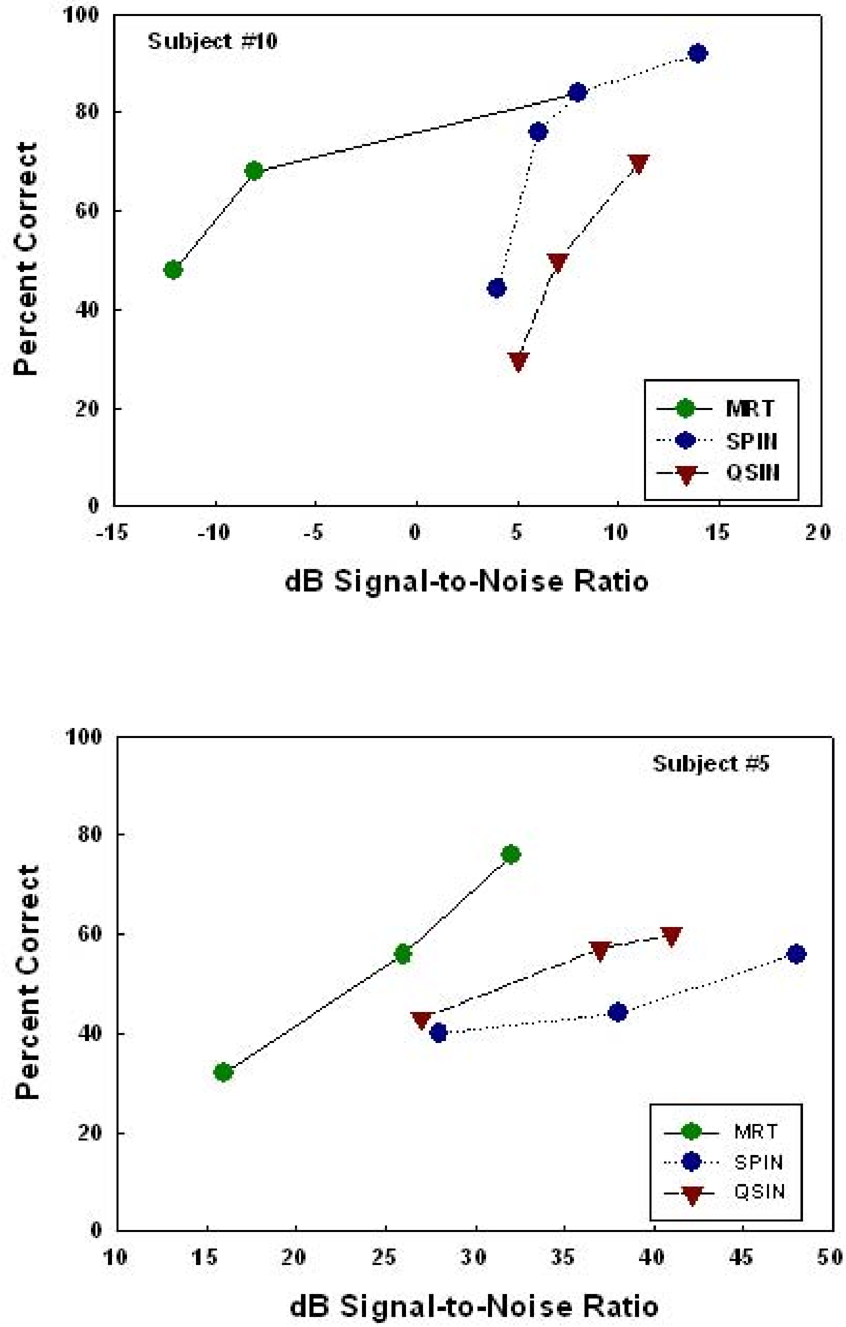

Figure 2.3. Psychometric functions for subject 10 (top) and subject 5 (bottom).

determine the SNRs needed to generate equal levels of performance across the three speech tests. As can be seen in Figure 2.3, subjects exhibited variability. Subject 10's psychometric functions were steep. Subject 5's psychometric functions were shallow. In the interest of time and subject fatigue, half lists of the tests were administered at each SNR. In other words, subjects were presented 25 items from the MRT, 25 sentences from the SPIN, and 6 sentences from the QSIN at various SNRs until the 50%-correct threshold could be interpolated. Test tokens were delivered over a telephone line to a telephone receiver. The presentation order of the tests (MRT, SPIN, QSIN) was randomized to minimize order effects.

2.3.2 Session Two

When the participants came back for the second session, each subject listened to the MRT, SPIN, and QSIN with multitalker babble presented from loudspeakers under two conditions: unprocessed and processed (TSEA). In the unprocessed condition, the digitized test tokens were delivered to the listener over the telephone line in its original form without any processing. In the processed condition, the digitized test tokens were delivered to the listener over the telephone line using Comunify, the commercial signal processing server platform developed by FutureCom Technologies, which runs the TSEA. The tests were presented at the 50%-correct SNR determined in Session One. Each subject's recognition performance between the unprocessed and processed conditions was then compared in order to determine the effectiveness of the

TSEA at improving communication over the telephone. Unlike in Session One, full lists of each test (MRT, SPIN, QSIN) were administered to the subjects. In other words, participants were presented the full 50 items from the MRT, the full 50 sentences from the SPIN, and 12 sentences from the QSIN. Test tokens were again delivered over a telephone line to a telephone receiver. The presentation order of the tests was randomized to minimize order effects. In addition, several versions of the MRT, SPIN, and QSIN were administered so that subjects did not hear a particular version more than once between the two sessions. All subjects used the same ear to listen to the test materials during Session Two that they used during Session One.

CHAPTER 3

RESULTS

The purpose of the current study was to equate the level of difficulty of the three speech perception tests (MRT, SPIN, QSIN) first, before measuring the effectiveness of the TSEA at improving speech intelligibility over the telephone at each level of speech (phoneme, word, and sentence) for older adults with hearing loss so that bias could be eliminated and performance of the TSEA could be isolated and measured.

3.1 Data Analysis

The data collected from this study were utilized to calculate percent correct scores as well as percent improvement scores for all twelve subjects on all three tests (MRT, SPIN, and QSIN). The subjects' individual scores for each test from Session One can be found in Appendix B. Data from Session One were used solely to estimate the 50%-correct threshold for each speech test and were not analyzed further. Individual scores for each test from Session Two can be found in Appendix C. Each subject's percent improvement between the unprocessed and processed conditions was analyzed to determine if the three speech perception tests resulted in statistically similar or different levels of performance.

3.2 Unprocessed vs. Processed Recognition Performance

Descriptive statistics (means and standard deviations) for the unprocessed and processed experimental conditions for each of the three tests (MRT, SPIN, and QSIN) are presented in Figure 3.1 and Table 3.1. As illustrated by Figure 3.1, mean recognition performance was better in the processed condition compared to the unprocessed condition for all speech tests. This point is also evident when looking at the individual data for both the unprocessed and processed conditions. Figure 3.2 is a bivariate plot of individual datum points for each test with unprocessed recognition performance on the abcissa and processed recognition performance on the ordinate. As can be seen in Figure 3.2, all data points fall above the diagonal line, indicating superior recognition performance in the processed condition.

When looking specifically at the unprocessed condition, the results illustrate that the 50%-correct threshold interpolated for each function to generate equal levels of performance across the three speech tests was successful for both the SPIN and QSIN. However, subject performance for the MRT in the unprocessed condition still tended to result in performance above 50%, even after attempting to generate equal levels of performance among the three speech tests. Higher performance on the MRT could indicate either that the MRT is a less challenging test compared to the SPIN and QSIN, or that presenting only

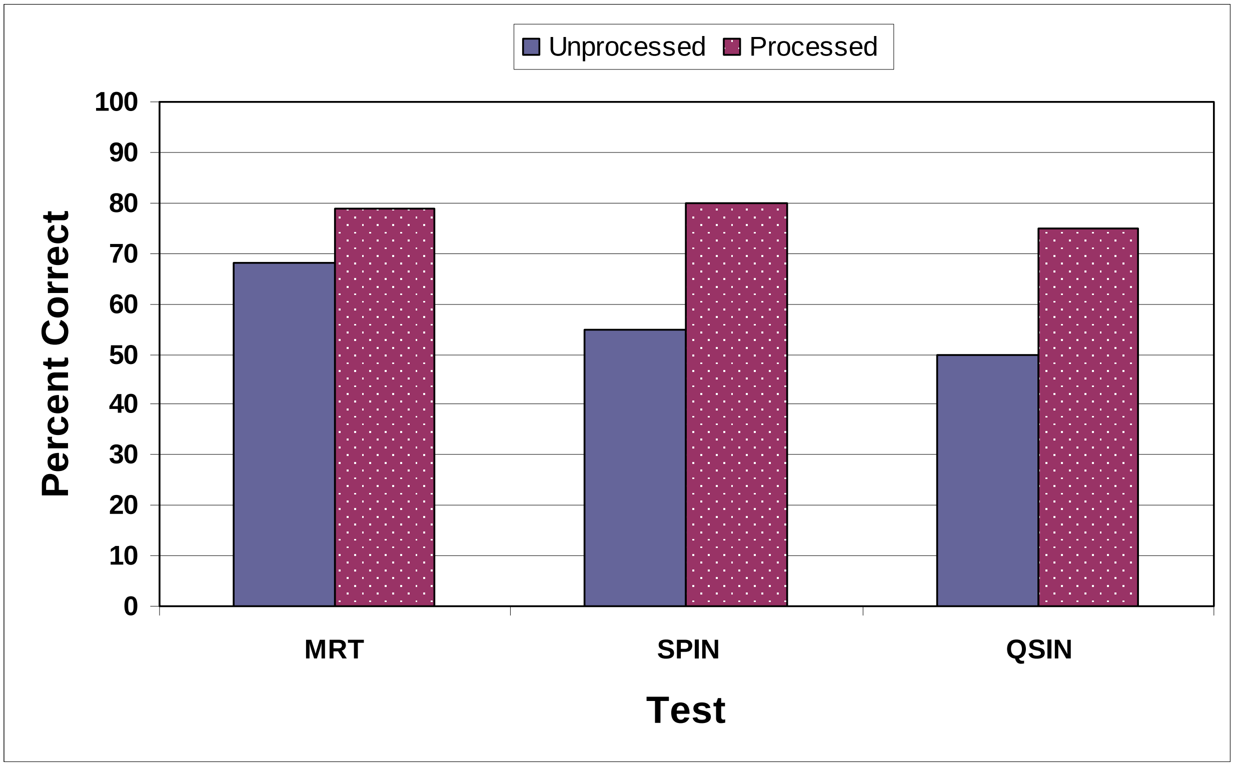

FIGURE 3.1. Average percent correct responses for unprocessed and processed presentations for each speech intelligibility test.

TABLE 3.1. Mean speech recognition performance (in percent) for the three speech tests (MRT, SPIN and QSIN) across the two listening conditions: unprocessed and processed.

	MRT %	SPIN %	QSIN %
Unprocessed			
Mean	68.2	55.2	49.9
SD	(5.2)	(9.4)	(16.6)
Range	16	30	54
Processed			
Mean	79.0	79.8	75.0
SD	(9.0)	(7.1)	(15.0)
Range	24	22	53

SD = standard deviation

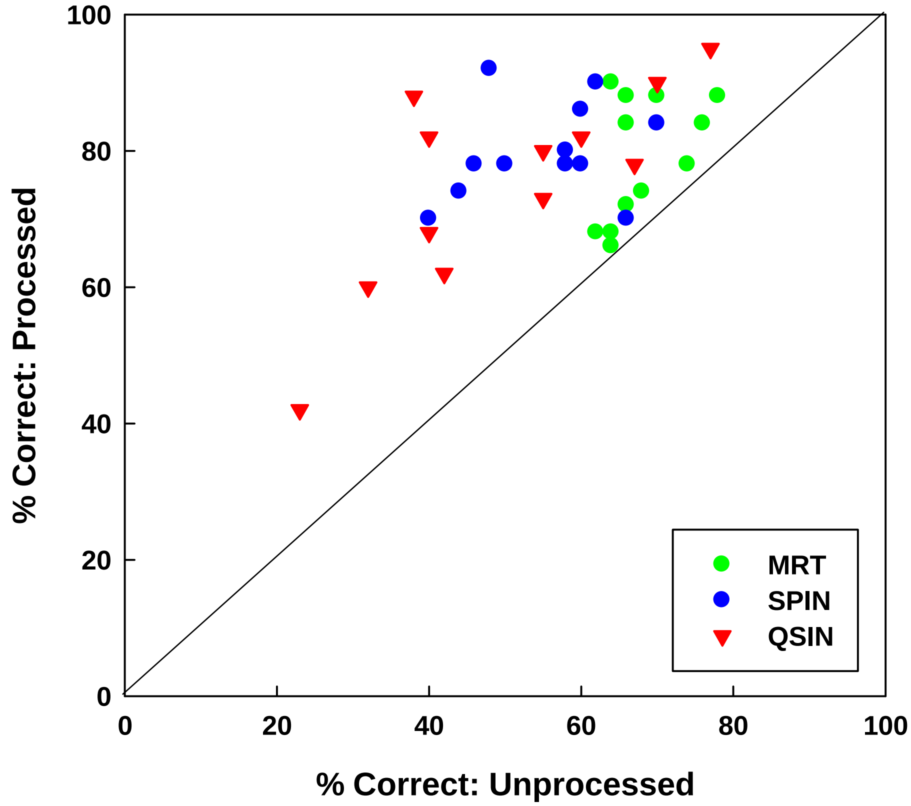

Figure 3.2. Individual performance for each subject for the MRT, SPIN, and QSIN. All points fall above the diagonal line, indicating that all subjects performed better in the processed condition compared to the unprocessed condition for all three tests.

half lists rather than full 50 token lists during Session One biased MRT performance without biasing SPIN and QSIN performance. As a result, the largest differences between scores obtained for the unprocessed compared to processed conditions occurred with the SPIN and QSIN. A smaller difference was found when comparing the unprocessed to the processed condition for the MRT. This information is illustrated in Figure 3.3.

Prior to further statistical analysis, the percentage data were arc-sine transformed (Studebaker, 1985) and analyzed using a two-factor (*test and condition*) within-subject analysis of variance (ANOVA). A significant main effect of *test* was found ($F_{1,11}$ =74; $p<.05$). Post hoc analysis using paired samples t-tests (with Bonferroni correction) indicated significant differences between tests. For the unprocessed condition, performance on the MRT was significantly better than the SPIN ($t_{11} = 5.6$; $p<.008$) and the QSIN ($t_{11} = 8.8$; $p<.008$). Similarly, performance on the SPIN was significantly better than the QSIN ($t_{11} = 5.1$; $p<.008$). For the processed condition, post hoc analysis indicated that performance on the QSIN was significantly worse than either the MRT ($t_{11} = 4.5$; $p<.008$) or the SPIN ($t_{11} = 4.9$; $p<.008$).

In addition to a main effect of test, the ANOVA also indicated a significant main effect of *condition* ($F_{1,11}$ =119; $p<.05$). Post hoc analysis using paired samples t-tests (with Bonferroni correction) indicated significant differences in recognition performance for all tests. Specifically, performance was significantly better in the processed condition for the MRT ($t_{11} = -4.5$; $p<.017$), the SPIN ($t_{11} = -8.2$; $p<.017$), and the QSIN ($t_{11} = -4.4$; $p<.017$).

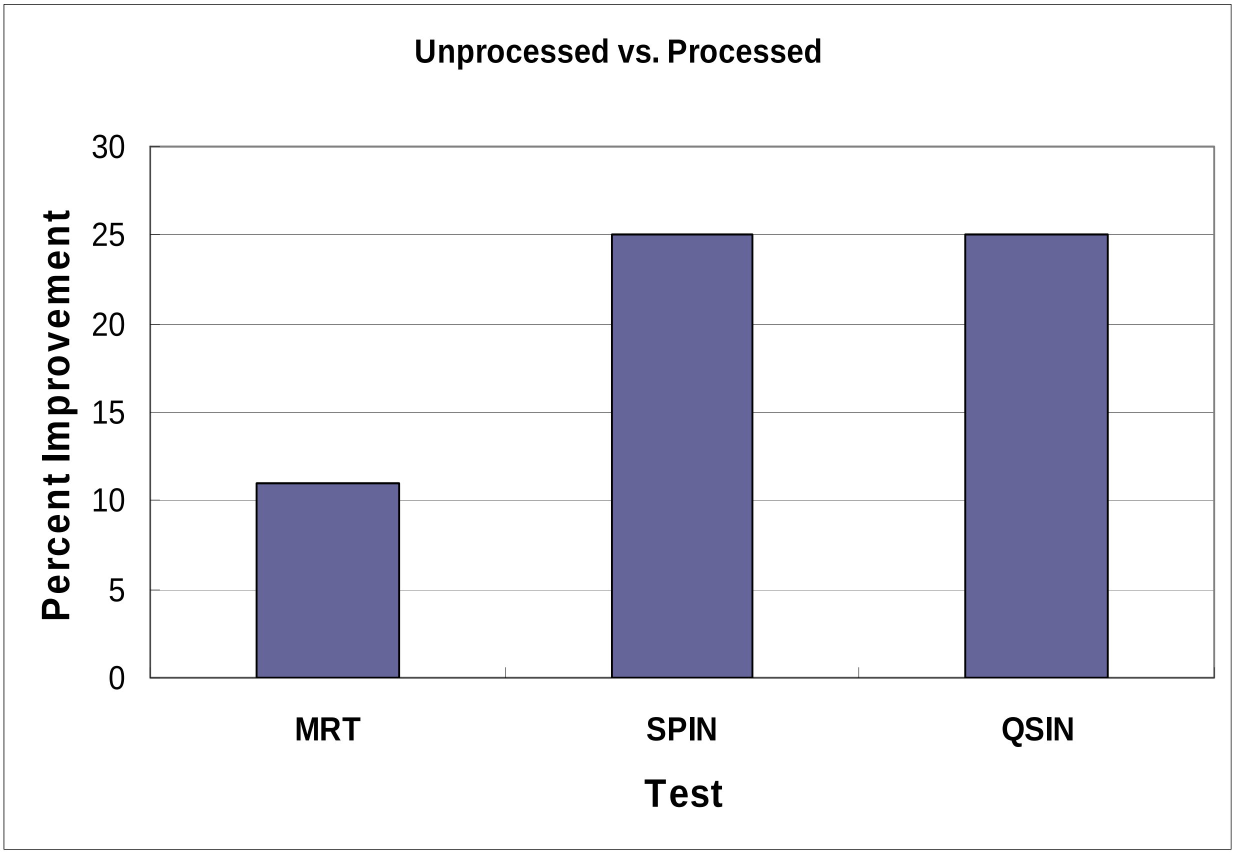

FIGURE 3.3. Average percent improvement in the processed condition compared to the unprocessed condition for each speech intelligibility test.

Finally, a significant interaction effect between *test* and *condition* was found ($F_{2,22} = 3.6$; $p<.05$), indicating the effect of processing was not the same across speech intelligibility tests. This is clearly illustrated in Figure 3.3, which presents the mean improvement in recognition performance as a function of test. Specifically, the percent improvement refers to the difference in mean scores between the processed and unprocessed conditions. As can be seen in Figure 3.3, processing of the speech resulted in less of an improvement in recognition performance for the MRT (10.8%) relative to the SPIN (24.6%) and QSIN (25.1%).

CHAPTER 4

DISCUSSION AND CONCLUSIONS

The ability to communicate effectively over the phone is taken for granted by most individuals. However, telephone communication is often difficult for older adults, who are more likely to suffer from hearing loss. Telephone communication is difficult for hearing-impaired listeners for a variety of reasons such as the lack of visual cues from the speaker, the diminished quality of the speech signal transmitted across the telephone line, the presence of background noise, and the fact that only one ear is utilized when communicating over the telephone (Kepler et al., 1992). Not surprisingly, these challenges can discourage hearing-impaired individuals from using the telephone, which can be especially devastating to older adults who are homebound and rely on the telephone for independence, self-esteem, safety, and socialization. Although the use of hearing aids and telecoils assist in telephone communication, many hearing aid users still struggle to communicate over the telephone. In addition, an estimated 25% of individuals over the age of 65 have a significant hearing loss (Yueh et al., 2003), but less than a quarter of individuals who could benefit from hearing aids actually own them (NCHAM, 2004). The number of older adults with hearing loss is expected to expand since the 65 years of age and older group is currently the fastest growing age group in the United States (AAA, 2007). In order to improve speech communication over the telephone among older adults, the TSEA was created to pre-process the speech at the talker's end to enhance it before being sent across the telephone line to the hearing-impaired listener. This study examined the effectiveness of the TSEA at improving the telephone speech understanding among older adults with hearing loss.

4.1 Summary of the Experiment

The main objective of the study was to attempt to equate the level of difficulty between the three speech tests utilized in Harhager's (2007) study (MRT, SPIN, and QSIN), which takes into account the three levels of speech perception (phoneme, word, and sentence, respectively). Specifically, multi-talker babble was added to the MRT and SPIN tests in both the unprocessed and processed conditions in an attempt to eliminate the ceiling effects of these tests found in Harhager's (2007) study. Subjects' performances from the unprocessed and processed presentations of the tests (MRT, SPIN, and QSIN) were then examined to determine if the hearing-impaired, older adults performed better when the speech was pre-processed with the TSEA compared to the unprocessed condition.

In order to equate the level of difficulty between tests, the 50%-correct threshold was interpolated in the unprocessed test condition after multitalker babble was added to both the MRT and SPIN tests. However, the 50%-correct interpolation was more successful for the QSIN compared to the MRT and the SPIN, indicating a significant effect of test. Subject performance for the MRT still tended to illustrate higher performance compared to both the SPIN and QSIN, while subject performance for the SPIN was significantly higher compared to the QSIN. Specifically, mean unprocessed performance was 68.2% for the MRT, 55.2% for the SPIN, and 49.9% for the QSIN.

Subjects' understanding over the telephone when the signal was pre-processed with the TSEA compared to the unprocessed condition was also examined. Results indicated that higher performance scores were obtained in the processed condition for all tests. Specifically, mean performance improved by 10.8% for the MRT, 24.6% for the SPIN, and 25.1% for the QSIN and indicated a significant improvement of performance for all three tests. These results are in agreement with previous research. For instance, Harhager (2007) found that mean performance improvements were noted for the MRT (4.7%), SPIN (10.9%), and QSIN (31.9%) when using the telephone speech enhancement algorithm. In addition, Terry et al. (1992) used both frequency shaping and frequency shaping with compression to take into account a hearing loss and improve understanding of speech filtered between 300 Hz – 3000 Hz, much like a true telephone. The California Consonant Test (CCT), a phoneme test, was used and an 11.8% and 15.8% improvement was noted for frequency shaping alone and frequency shaping with compression respectively (Terry et al., 1992). Unlike the Terry et al. (1992) study, the current study presents MRT, SPIN, and QSIN test tokens across a true telephone line monaurally to hearing-impaired listeners. The results of this study illustrate that the TSEA provided improved speech understanding over the telephone compared to the unprocessed condition. In other words, the TSEA was successful at improving telephone communication among older, hearing-impaired adults.

The subjects' telephone understanding in the unprocessed and processed test conditions were further examined to determine if the effect of processing was equivalent across the speech intelligibility tests. While percent improvement scores were relatively equal between the SPIN and QSIN tests, less improvement was noted for the MRT test. Specifically, mean recognition improvement in the processed condition was 10.8% for the MRT relative to 24.6% for the SPIN and 25.1% for the QSIN. These results suggest that the addition of multitalker babble in both the unprocessed and processed testing conditions successfully equated the level of difficulty between the SPIN and the QSIN. In other words, the ceiling effect illustrated for the SPIN test in previous research (Harhager, 2007) was eliminated. However, possible ceiling effects were still noted for the MRT based on the higher mean performance in the unprocessed condition and lower mean recognition improvement in the processed condition.

4.2 Suggestions for Future Research

Previous research with the TSEA has been promising. The speech processing algorithm has been illustrated to improve speech understanding of older adults with hearing loss over the telephone. In addition, FutureCom

Technologies, Inc. has successfully created a commercial version of the speech processing algorithm utilizing their Comunify platform. As a result of these successes, future research is planned. Specifically, Phase II of the SBIR grant includes several objectives.

First, the speech processing algorithm will be examined to determine if future improvements can be made. The original algorithm utilized in the TSEA will be examined to determine if adding additional hearing loss configurations such as a rising sensorineural hearing loss and a flat sensorineural hearing loss will provide further improvements. In other words, these specially created hearing loss configurations will be compared to the general sloping sensorineural hearing loss configuration to determine if more benefit is provided. In addition, the TSEA has been tested using only a standard telephone line to date. The speech processing algorithm will be tested on cell phones to determine if the benefit provided by the TSEA remains stable or declines. A third way that the speech processing algorithm will be tested is by examining how different male and female talkers affect the performance of the TSEA.

Another objective of future research is to create a version of the TSEA that is in real-time and can be placed in a commercial telephone network environment where multiple simultaneous callers interact with live talkers.

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APPENDIX A

AUDIOMETRIC DATA FOR EACH INDIVIDUAL SUBJECT

	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	PTA	SRT	W.R. %
Right	**45**	**60**	**60**	**60**	**35**	**5**	60	60	92
Left	**50**	**60**	**55**	**55**	**40**	**15**	67	60	92

TABLE A.1: Audiometric data for subject 1.
Ear used during testing: Left

	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	PTA	SRT	W.R. %
Right	**15**	**20**	**30**	**45**	**50**	**70**	32	25	92
Left	**15**	**20**	**30**	**45**	**40**	**70**	32	30	96

TABLE A.2: Audiometric data for subject 2.
Ear used during testing: Left

	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	PTA	SRT	W.R. %
Right	**30**	**30**	**50**	**65**	**70**	**60**	48	45	92
Left	**30**	**30**	**50**	**65**	**70**	**60**	48	40	92

TABLE A.3: Audiometric data for subject 3.
Ear used during testing: Left

	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	PTA	SRT	W.R. %
Right	**25**	**30**	**40**	**45**	**50**	**45**	38	40	100
Left	**25**	**35**	**40**	**55**	**55**	**55**	43	45	96

TABLE A.4: Audiometric data for subject 4.
Ear used during testing: Left

	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	PTA	SRT	W.R. %
Right	**55**	**55**	**55**	**50**	**60**	**95**	53	60	96
Left	**55**	**55**	**60**	**60**	**60**	**80**	58	60	96

TABLE A.5: Audiometric data for subject 5.
Ear used during testing: Left

	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	PTA	SRT	W.R. %
Right	**20**	**20**	**35**	**50**	**60**	**85**	35	45	96
Left	**30**	**30**	**50**	**55**	**70**	**90**	45	50	88

TABLE A.6: Audiometric data for subject 6.
Ear used during testing: Left

	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	PTA	SRT	W.R. %
Right	**60**	**60**	**55**	**65**	**75**	**NR**	60	65	68
Left	**60**	**60**	**75**	**75**	**110**	**NR**	70	75	56

TABLE A.7: Audiometric data for subject 7.
Ear used during testing: Right

	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	PTA	SRT	W.R. %
Right	**30**	**35**	**35**	**35**	**55**	**75**	35	40	92
Left	**30**	**35**	**40**	**35**	**60**	**70**	37	40	92

TABLE A.8: Audiometric data for subject 8.
Ear used during testing: Left

	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	PTA	SRT	W.R. %
Right	**20**	**35**	**55**	**70**	**50**	**75**	53	60	88
Left	**30**	**40**	**60**	**70**	**65**	**80**	57	60	88

TABLE A.9: Audiometric data for subject 9.
Ear used during testing: Left

	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	PTA	SRT	W.R. %
Right	**50**	**45**	**35**	**45**	**55**	**80**	42	45	96
Left	**30**	**25**	**25**	**35**	**60**	**75**	28	35	92

TABLE A.10: Audiometric data for subject 10.
Ear used during testing: Left

	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	PTA	SRT	W.R. %
Right	**15**	**25**	**30**	**55**	**70**	**70**	37	DNT	68
Left	**20**	**25**	**35**	**60**	**70**	**65**	38	DNT	64

TABLE A.11: Audiometric data for subject 11.
Ear used during testing: Left

	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	PTA	SRT	W.R. %
Right	**45**	**50**	**65**	**60**	**65**	**90**	58	DNT	DNT
Left	**55**	**45**	**50**	**65**	**65**	**85**	53	DNT	DNT

TABLE A.12: Audiometric data for subject 12.
Ear used during testing: Left

	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	PTA	SRT	W.R. %
Right	**50**	**50**	**55**	**60**	**70**	**80**	55	DNT	52
Left	**40**	**45**	**45**	**55**	**65**	**85**	48	DNT	64

TABLE A.13: Audiometric data for subject 13.
Ear used during testing: Left

	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	PTA	SRT	W.R. %
Right	**20**	**30**	**30**	**60**	**70**	**65**	40	DNT	64
Left	**35**	**30**	**25**	**60**	**60**	**55**	38	DNT	80

TABLE A.14: Audiometric data for subject 14.
Ear used during testing: Left

APPENDIX B

INDIVIDUAL SCORES FROM SESSION ONE

Subject	Unprocessed SNR1 % Correct	Unprocessed SNR2 % Correct	Unprocessed SNR3 % Correct	Unprocessed SNR4 % Correct
1	28	44	68	
2	84	80	76	44
3	84	60	52	48
4	76	84	64	40
5	32	56	76	
6	68	56	48	
7	CNT	CNT	CNT	CNT
8	92	60	48	64
9	64	80	72	48
10	84	72	68	48
11	72	52	28	
12	80	64	48	
13	84	48	68	
14	76	52	36	

TABLE B.1. Individual scores on the MRT from Session One.

Subject	Unprocessed SNR1 % Correct	Unprocessed SNR2 % Correct	Unprocessed SNR3 % Correct	Unprocessed SNR4 % Correct
1	28	12	36	28
2	76	52	40	
3	40	48	68	
4	64	48	44	
5	40	44	56	
6	72	64	48	
7	DNT	DNT	DNT	
8	72	60	44	
9	36	64	68	
10	92	44	84	76
11	40	56	68	
12	36	48	66	
13	72	56	48	
14	52	48	68	

TABLE B.2. Individual scores on the SPIN from Session One.

Subject	Unprocessed SNR1 % Correct	Unprocessed SNR2 % Correct	Unprocessed SNR3 % Correct	Unprocessed SNR4 % Correct
1	DNT	DNT	DNT	
2	33	57	70	
3	40	48	68	
4	83	67	30	
5	43	57	60	
6	37	60	70	
7	DNT	DNT	DNT	
8	77	20	67	
9	33	37	53	
10	30	70	50	
11	40	47	60	
12	40	43	57	
13	70	27	47	
14	60	53	43	

TABLE B.3. Individual scores on the QSIN from Session One.

APPENDIX C

INDIVIDUAL SCORES FROM SESSION TWO

Subject	50% SNR	Unprocessed % Correct	Processed % Correct	% Improvement
1	DNT	DNT	DNT	DNT
2	-15	66	84	27
3	2	66	88	33
4	-8	74	78	5
5	24	64	90	41
6	-9	64	68	6
7	DNT	DNT	DNT	DNT
8	-5	78	88	13
9	3	70	88	26
10	-12	76	84	11
11	2	64	66	3
12	5	62	68	10
13	-2	66	72	9
14	-3	68	74	9

TABLE C.1. Individual scores on the MRT from Session Two.

Subject	50% SNR	Unprocessed % Correct	Processed % Correct	% Improvement
1	DNT	DNT	DNT	DNT
2	-8	60	86	43
3	19	46	78	70
4	3	70	84	20
5	43	50	78	56
6	12	58	80	38
7	DNT	DNT	DNT	DNT
8	-1	62	90	45
9	27	66	70	6
10	4	48	92	92
11	20	44	74	68
12	27	40	70	75
13	2	60	78	30
14	14	58	78	34

TABLE C.2. Individual scores on the SPIN from Session Two.

Subject	50% SNR	Unprocessed % Correct	Processed % Correct	% Improvement
1	DNT	DNT	DNT	DNT
2	-7	67	78	16
3	16	42	62	48
4	2	70	90	29
5	32	40	82	105
6	27	38	88	132
7	DNT	DNT	DNT	DNT
8	3	77	95	23
9	36	60	82	37
10	7	55	73	33
11	21	23	42	83
12	36	32	60	88
13	10	55	80	45
14		40	68	70

TABLE C.3. Individual scores on the QSIN from Session Two.